Damage Tolerance Behavior of Friction Stir Welds in Aluminum Alloys

Preston McGill
Jonathan Burkholder

Friction stir welding is a solid state welding process used in the fabrication of various aerospace structures. Self-reacting and conventional friction stir welding are variations of the friction stir weld process employed in the fabrication of cryogenic propellant tanks which are classified as pressurized structure in many spaceflight vehicle architectures. In order to address damage tolerance behavior associated with friction stir welds in these safety critical structures, nondestructive inspection and proof testing may be required to screen hardware for mission critical defects. The efficacy of the nondestructive evaluation or the proof test is based on an assessment of the critical flaw size. Test data describing fracture behavior, residual strength capability, and cyclic mission life capability of friction stir welds at ambient and cryogenic temperatures have been generated and will be presented in this paper. Fracture behavior will include fracture toughness and tearing (R-curve) response of the friction stir welds. Residual strength behavior will include an evaluation of the effects of lack of penetration on conventional friction stir welds, the effects of internal defects (wormholes) on self-reacting friction stir welds, and an evaluation of the effects of fatigue cycled surface cracks on both conventional and self-reacting welds. Cyclic mission life capability will demonstrate the effects of surface crack defects on service load cycle capability. The fracture data will be used to evaluate nondestructive inspection and proof test requirements for the welds.

Damage Tolerance Behavior of Friction Stir Welds in Aluminum Alloys

National Space and Missile Materials Symposium
June 2012

Preston McGill
Jonathan Burkholder

Materials and Processes Laboratory
NASA Marshall Space Flight Center

Acknowledgements

NASA Marshall Space Flight Center

C. Russell – Metal Joining and Processes Branch
S. Brooke – Metal Joining and Processes Branch
J. Littell – Metal Joining and Processes Branch (Jacobs Engineering)
R. Jones – Metal Joining and Processes Branch (Jacobs Engineering)
S. Cato – NASA/MSFC Failure Analysis and Metallurgy Branch
T. Malone – NASA/MSFC Materials Test Branch
R. Horton – NASA/MSFC Materials Test Branch
J. Hodo – NASA/MSFC Materials Test Branch
S. Russell – NASA/MSFC Damage Tolerance Assessment Branch
D. Ezell – NASA/MSFC Damage Tolerance Assessment Branch (Teledyne Brown Engineering)

Lockheed Martin Manned Space Systems
Michoud Assembly Facility

D. Kinchen – Material Science
M. Worden – Production Operations
N. Elfer – Material Science

Damage Tolerance

NASA Human Space Flight Requirements

- NASA safety requirements call for fault tolerance or a minimum risk approach for human rated flight hardware
- Damage tolerance is one element of a minimum risk approach
- Basic philosophy behind damage tolerance is mitigating risk associated with a part failing from a crack or crack-like defect

Damage Tolerance is a Multi-Disciplined Endeavor

- Design, analysis, NDE, process control, quality control, acceptance testing (proof testing) and material behavior
- Particular interest in behavior of material with cracks or crack-like defects

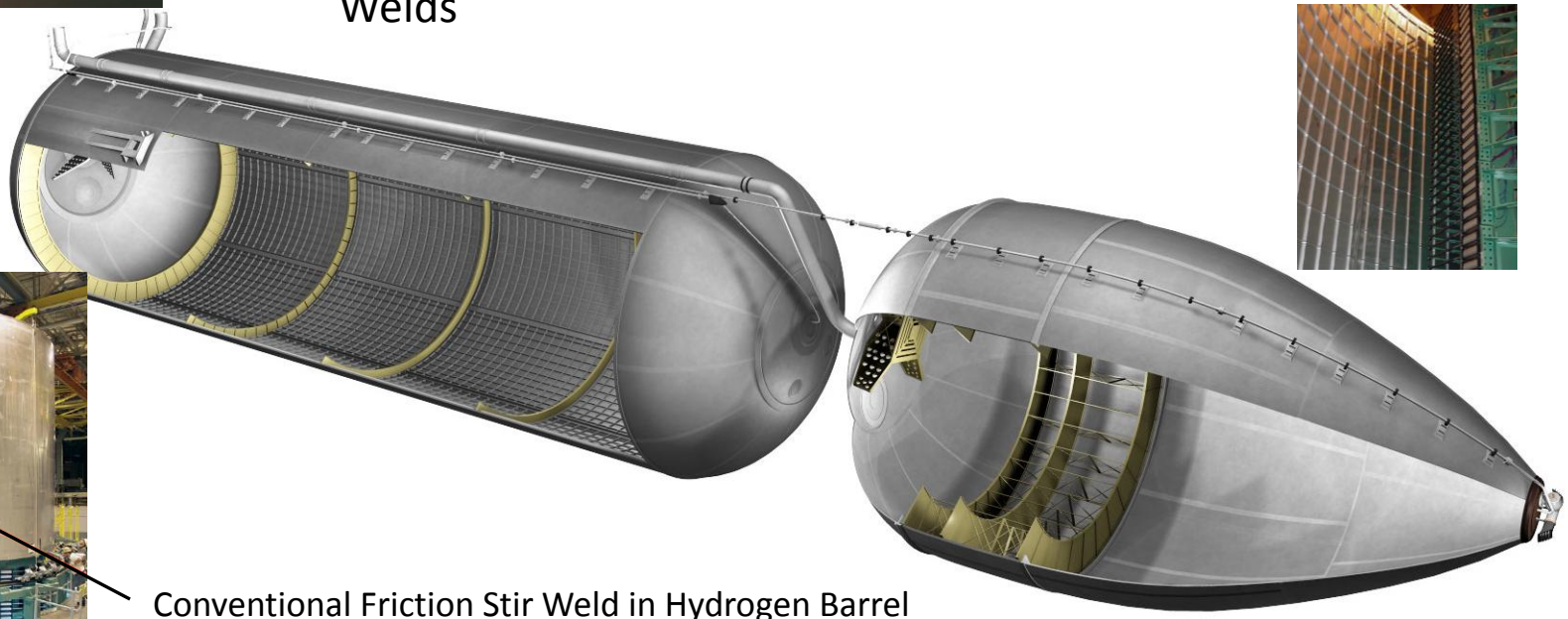
Damage Tolerance Approach

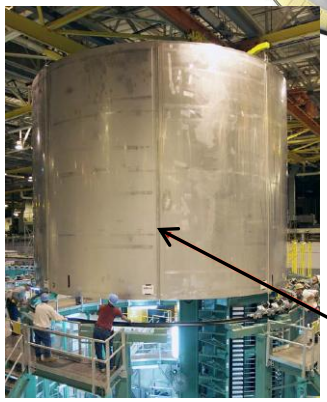
- Process Control
- Residual Strength Behavior
- Nondestructive Evaluation
- Proof Test

Applications

Space Shuttle External Tank

- Pressurized Structure
- Conventional Friction Stir Welds
  - ET 132, ET133 through ET 138
    - 2195/2195 Longitudinal Hydrogen Tank Barrel Welds
  - ET134 through ET 138
    - 2195/2195 Longitudinal Oxygen Tank Barrel Welds
    - 2219/2195 Longitudinal Longeron to Hydrogen Tank Barrel Welds



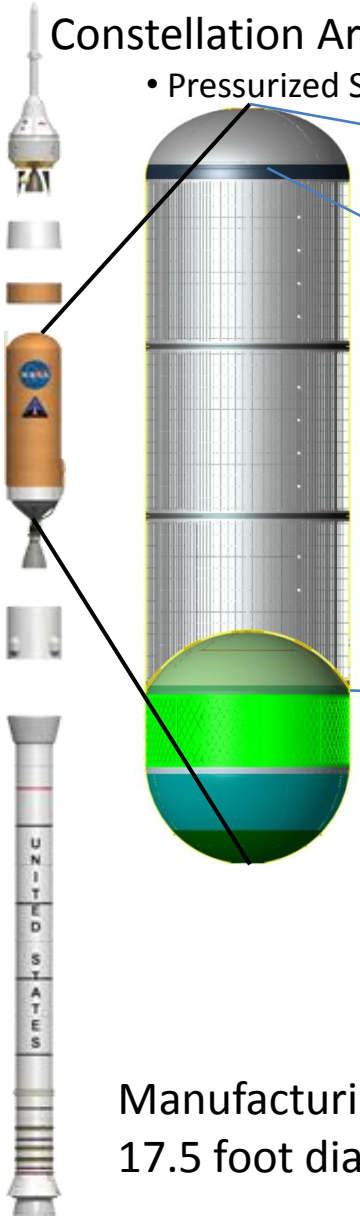


Conventional Friction Stir Weld in Hydrogen Barrel
Reference: Kinchen , 2008

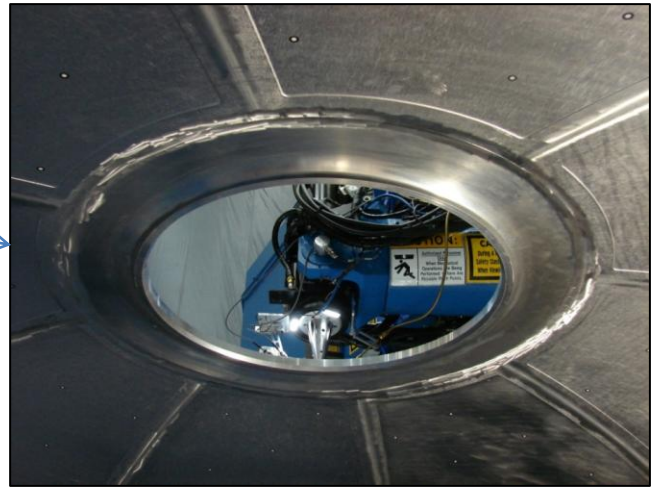
Applications

Constellation Ares I Propellant Tanks

- Pressurized Structure

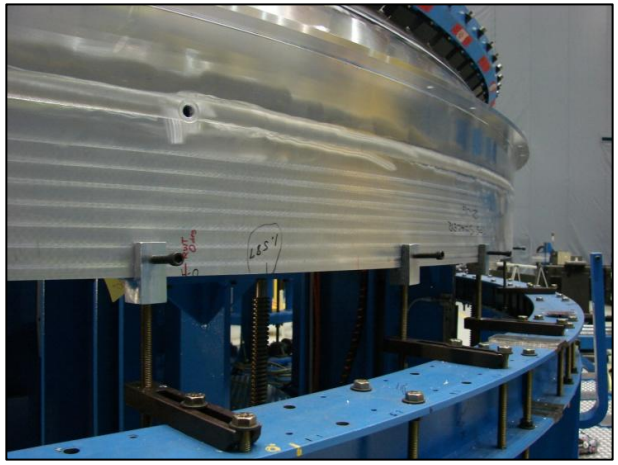


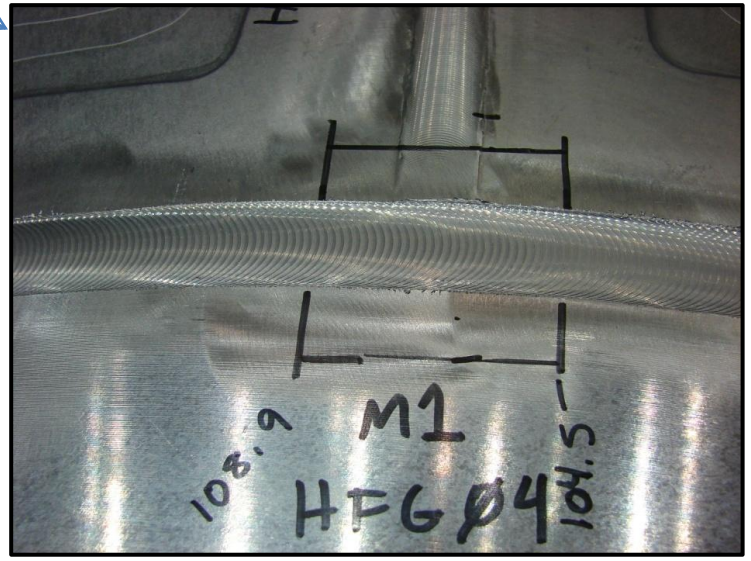
Conventional FSW



Self-Reacting FSW

Self-Reacting FSW with Termination Hole

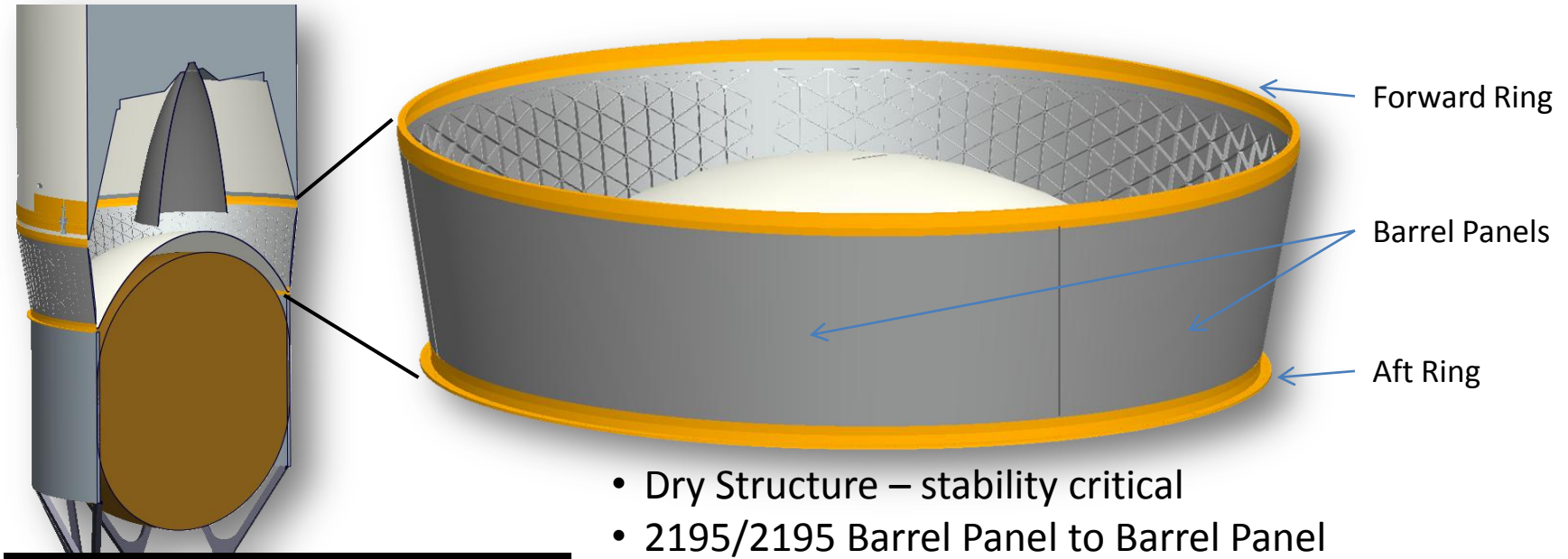


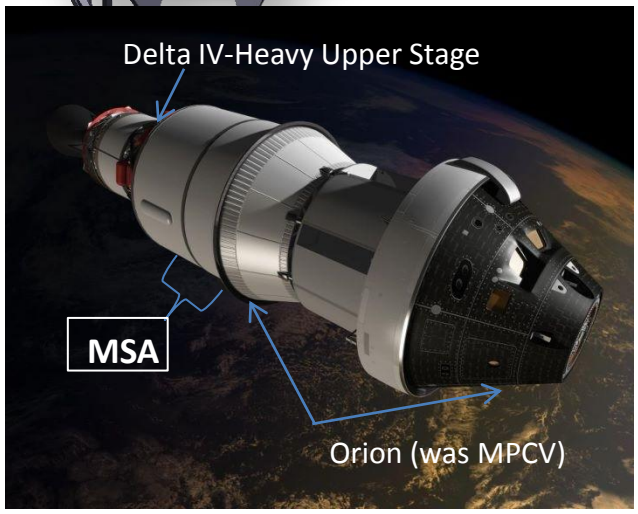


Manufacturing Demonstration Article
17.5 foot diameter

Applications

Space Launch System Multi-Purpose Crew Vehicle Stage Adaptor

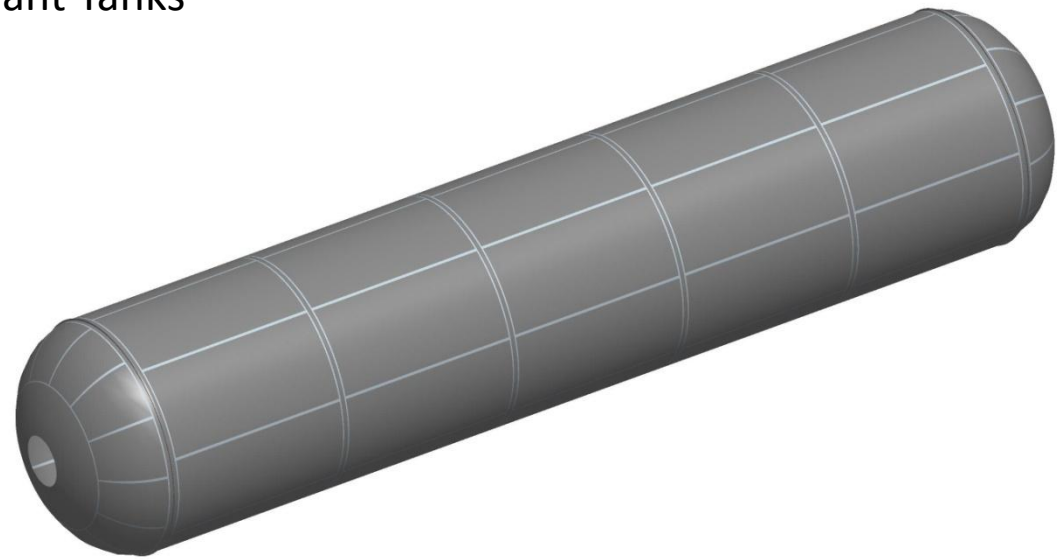




- Dry Structure – stability critical
- 2195/2195 Barrel Panel to Barrel Panel Longitudinal Conventional Friction Stir Welds
- 2219/2195 Forward and Aft Ring to Barrel Panel Self-Reacting Circumferential Friction Stir Welds
- 16 foot diameter aft end
- 18.5 foot diameter forward end
- Pathfinder in Work
- Structural Test Article in Work
- Engineering Flight Test Article in Work

Applications

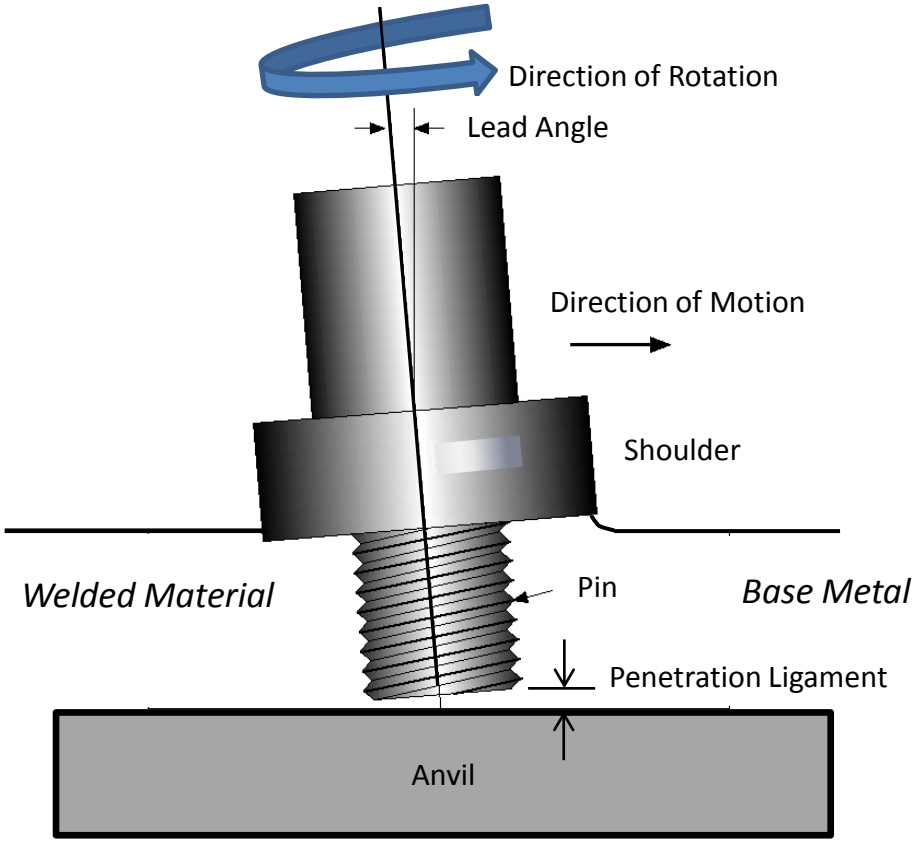
Space Launch System Propellant Tanks



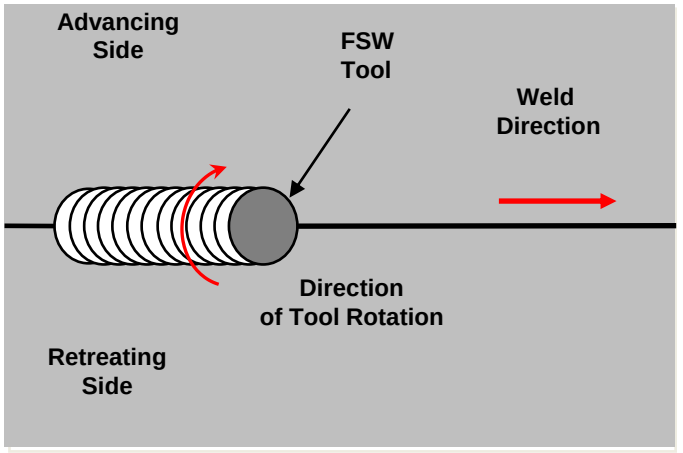
- Pressurized Structure
- Liquid Hydrogen Tank
- Liquid Oxygen Tank
- 100% Friction Stir Welded
- Weld Process in Work
- Design in Work

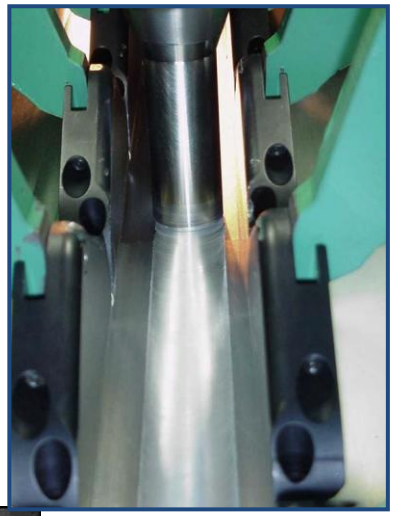
Processes

Conventional Friction Stir Weld



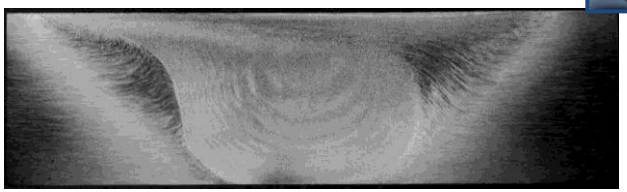
Ref: Nunes, 2011





Friction Stir Weld in Progress

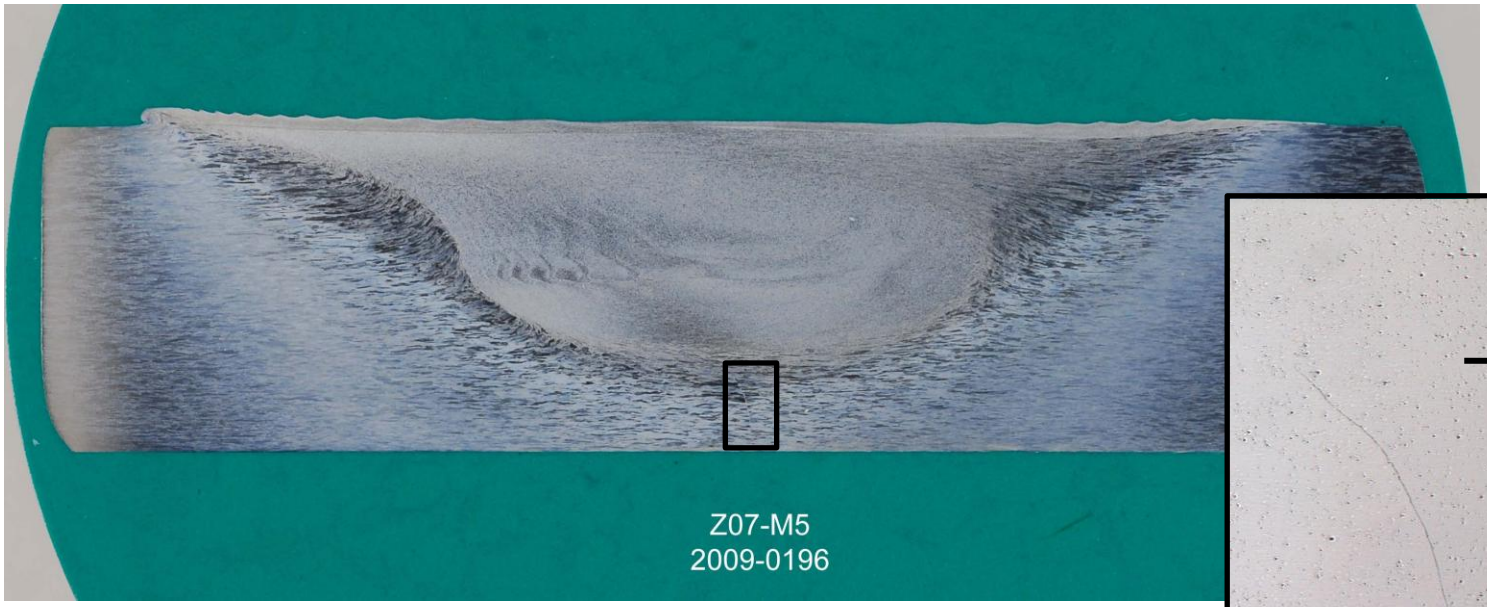
Reference: Kinchen , 2008

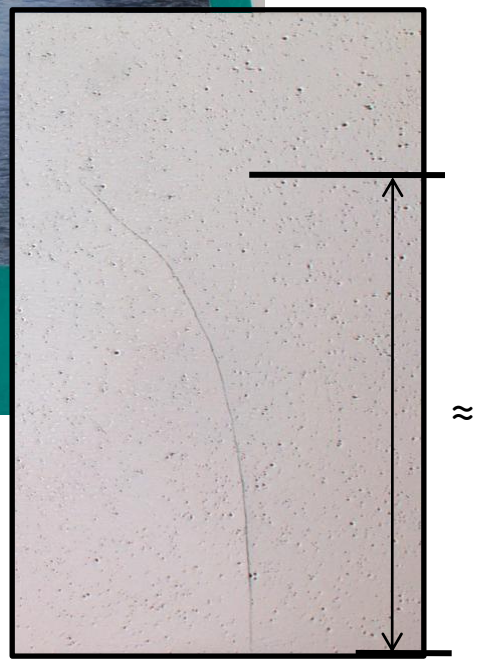


Nominal Transverse Cross Section

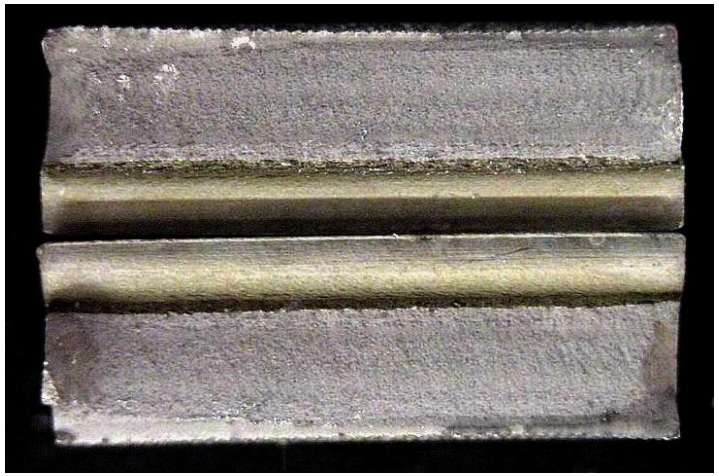
Processes

2195/2195 Conventional Friction Stir Weld with Lack of Penetration Defect, t = 0.320”





≈ 0.080”

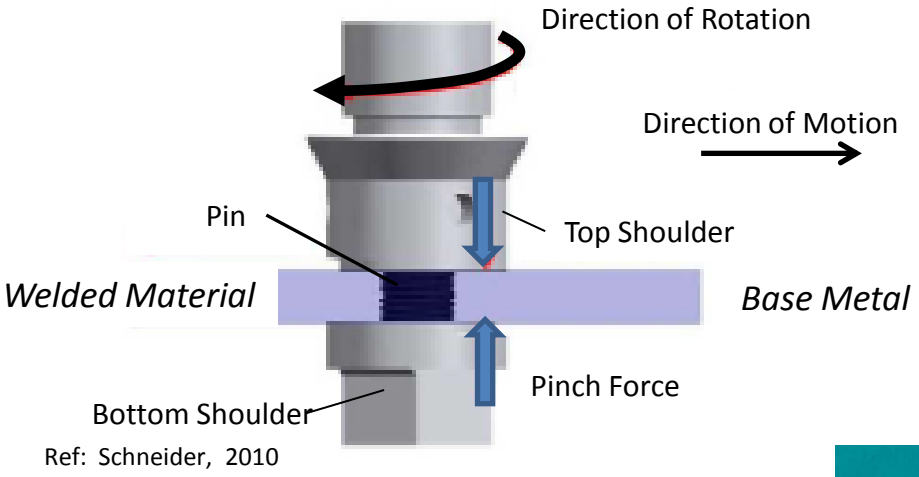


Test sample with fracture across LOP

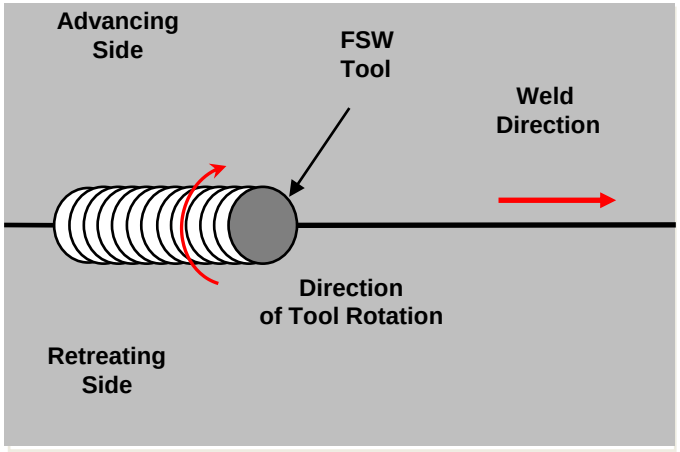
Ref: Kinchen, 2000

Processes

Self-Reacting Friction Stir Weld



Ref: Schneider, 2010

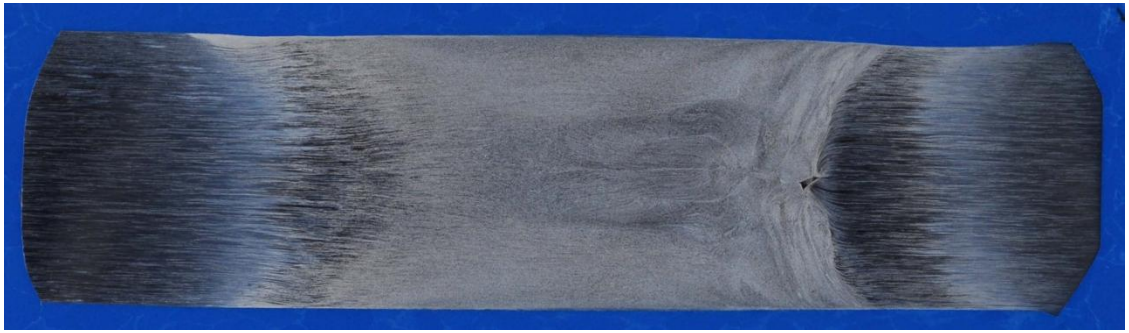


Self-Reacting Weld Tool

Nominal Transverse Cross Section

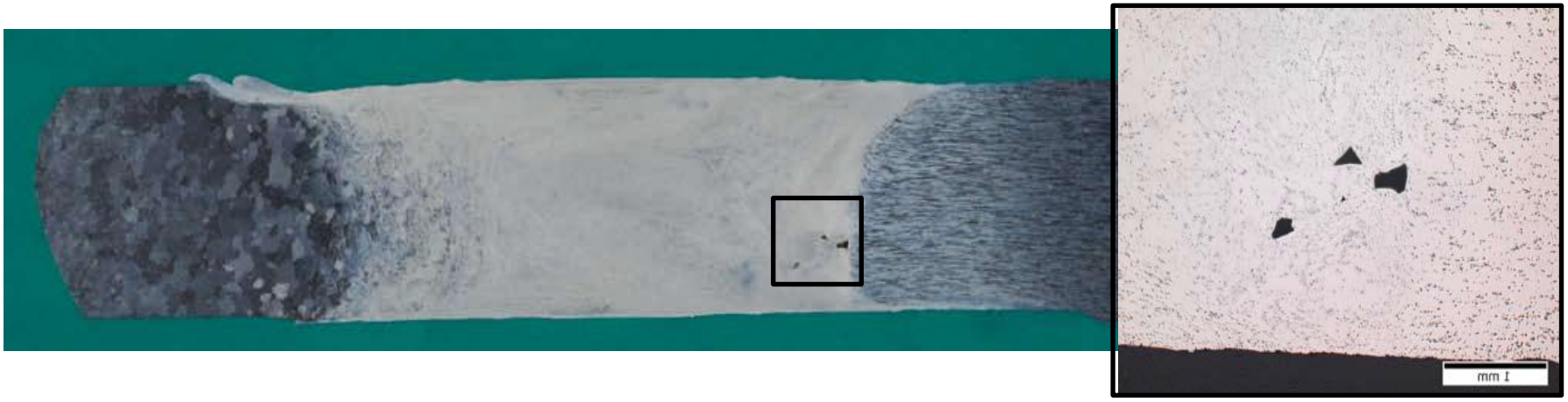
Processes

2195/2195 Self Reacting Friction Stir Weld with Wormhole Defect, t = 0.327”



Defect Size
0.025” x 0.013”

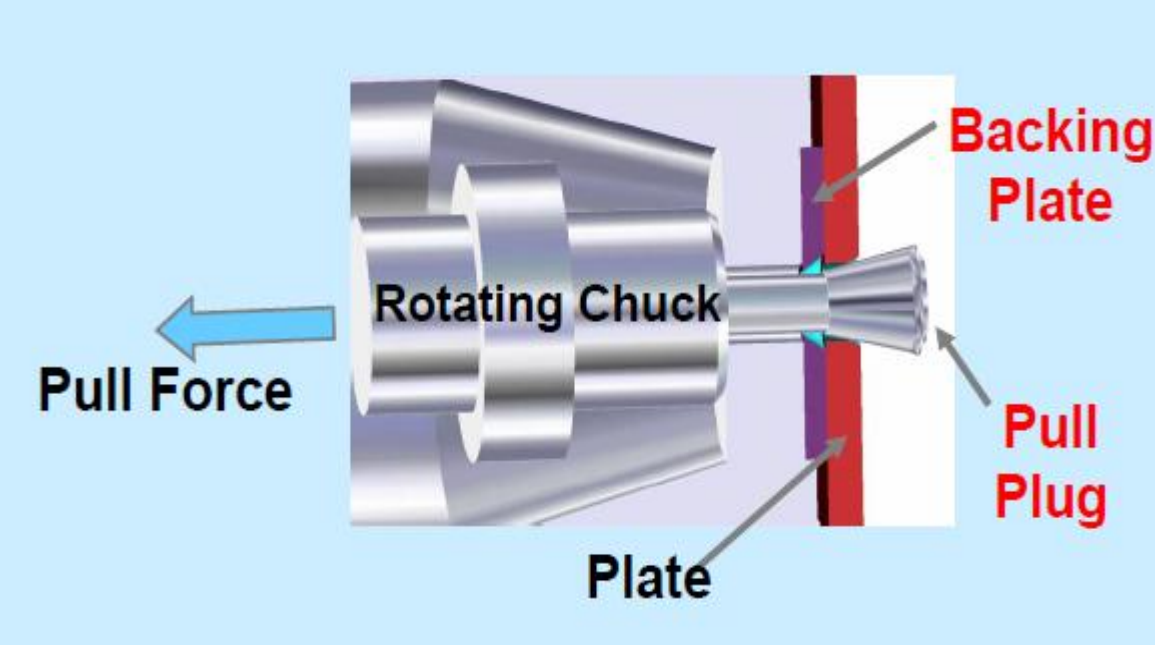
2219/2014 Self Reacting Friction Stir Weld with Wormhole Defect, t = 0.208”



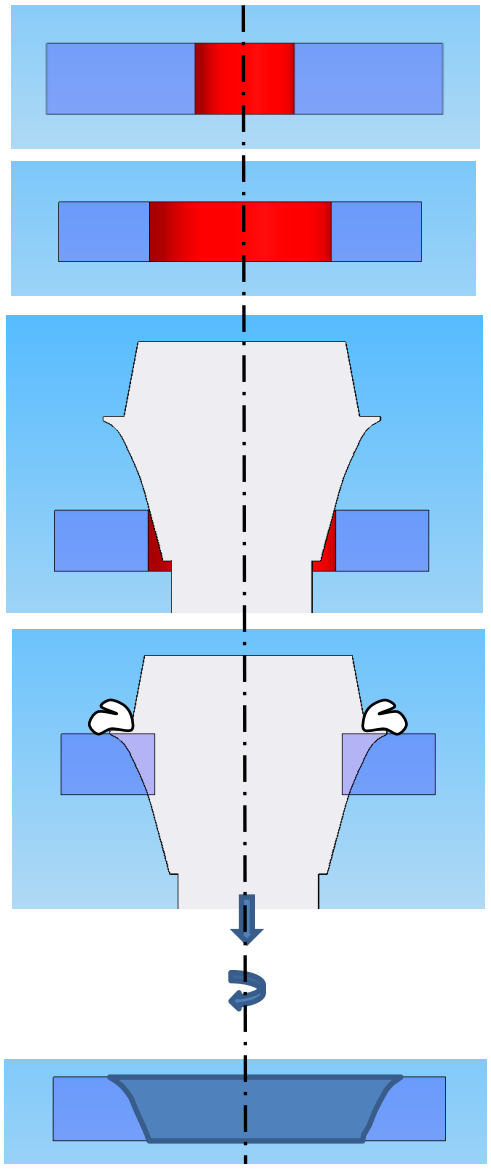
Defect Sizes: 0.013” x 0.010”; 0.007” x 0.010”; 0.010” x 0.005”

Processes

Friction Pull Plug Weld



Processes

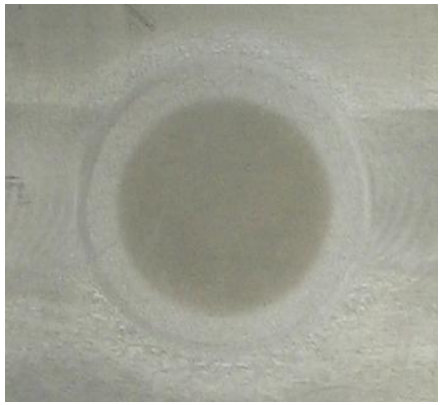


Self-reacting Friction Stir Weld Termination Hole

Hole Enlarged to Accommodate Pull Plug

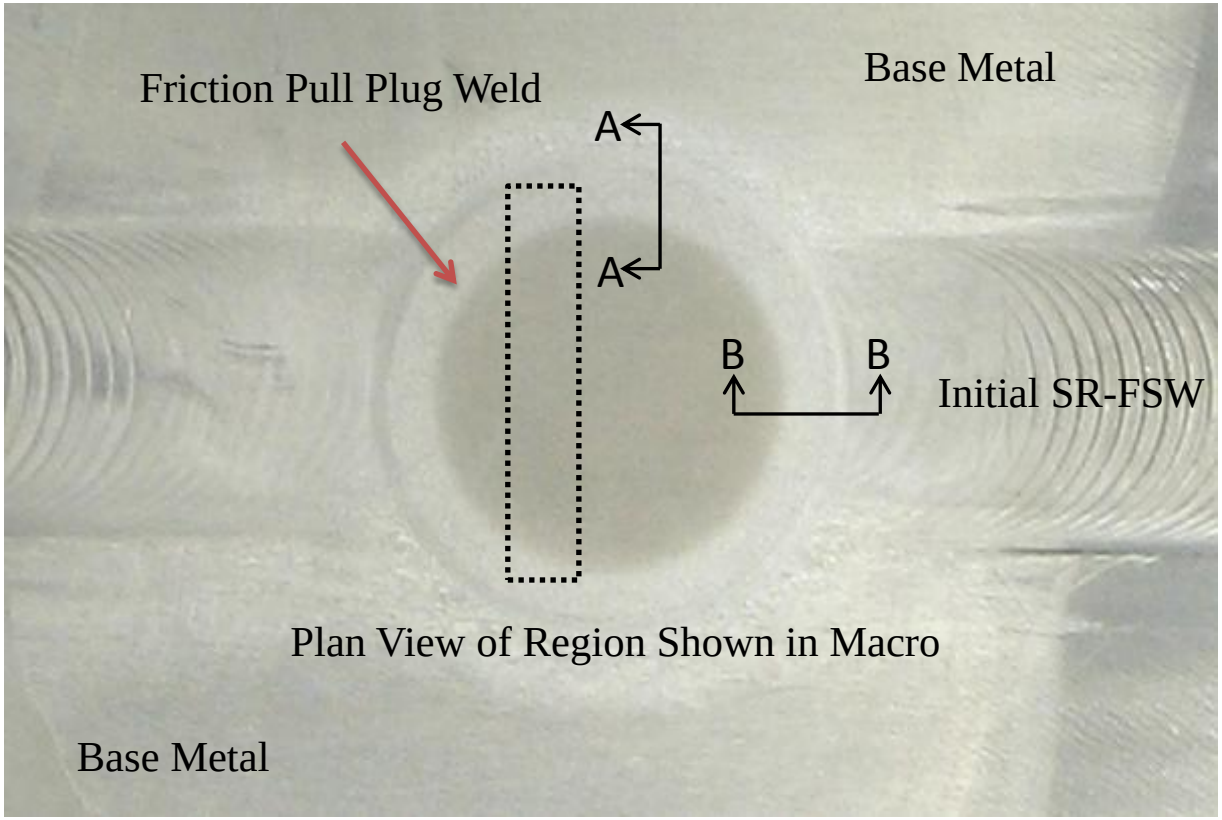
Pull Plug at “zero” Displacement

Pull Plug at “full” Displacement



Pull Plug after Final Machining

Processes

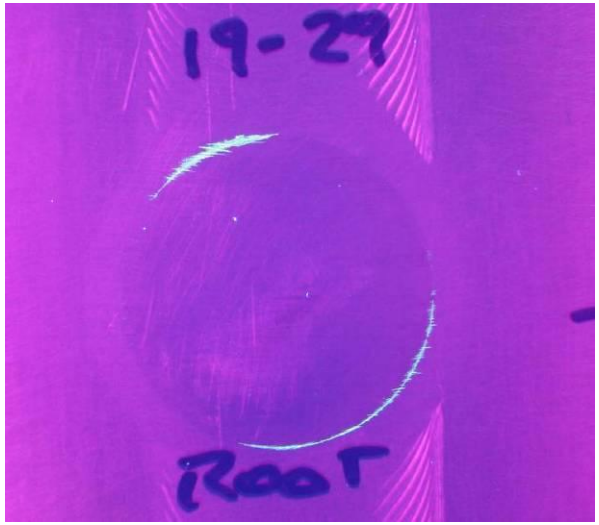


Cross Section A-A
Plug - Base Metal

Cross Section B-B
Plug - Friction Stir Weld

Processes

Defects in Friction Pull Plug Welding

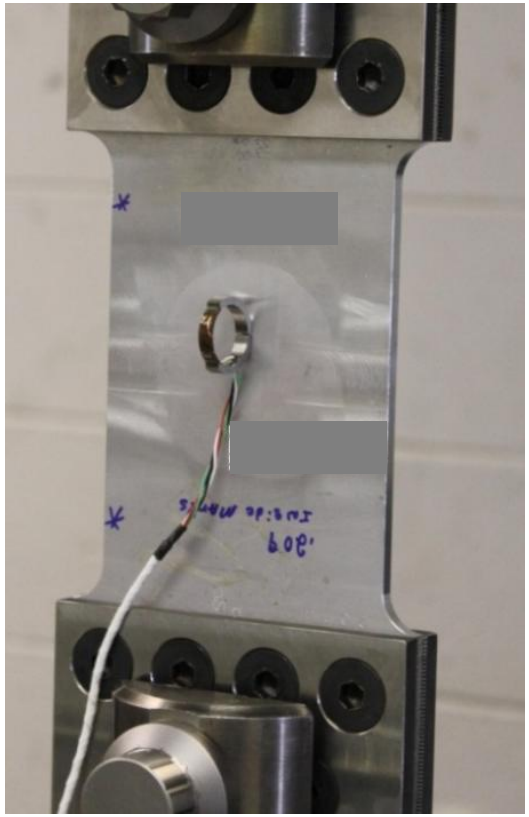


Ref: Kinchen, 2009

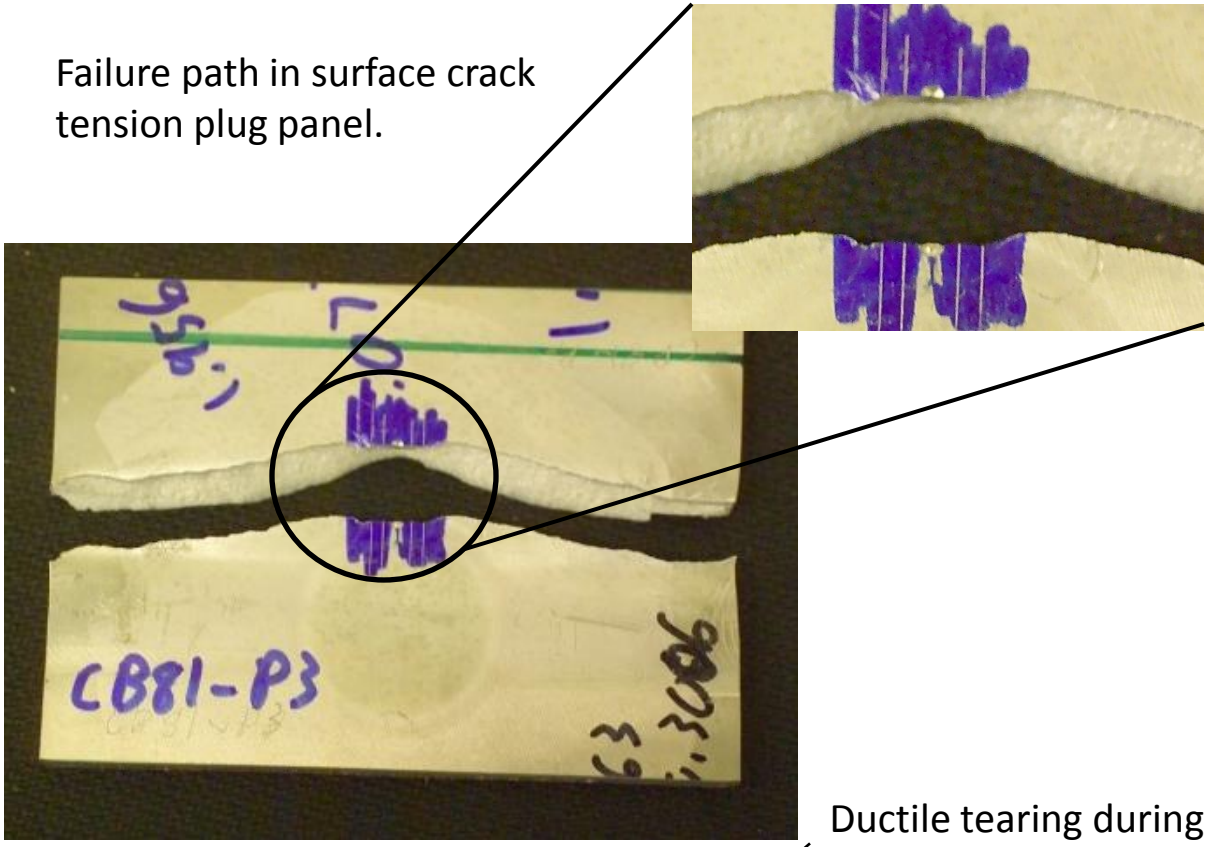
Liquid Penetrant indications

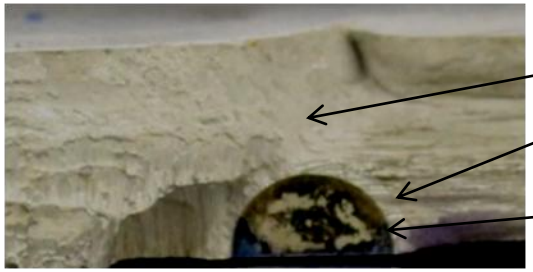
Testing

Surface Crack Tension Test Sample



Failure path in surface crack tension plug panel.



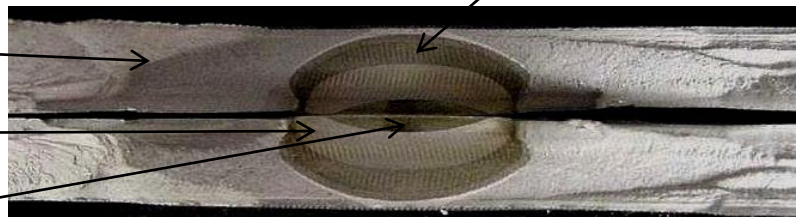


Fracture Surface

Fatigue Precrack

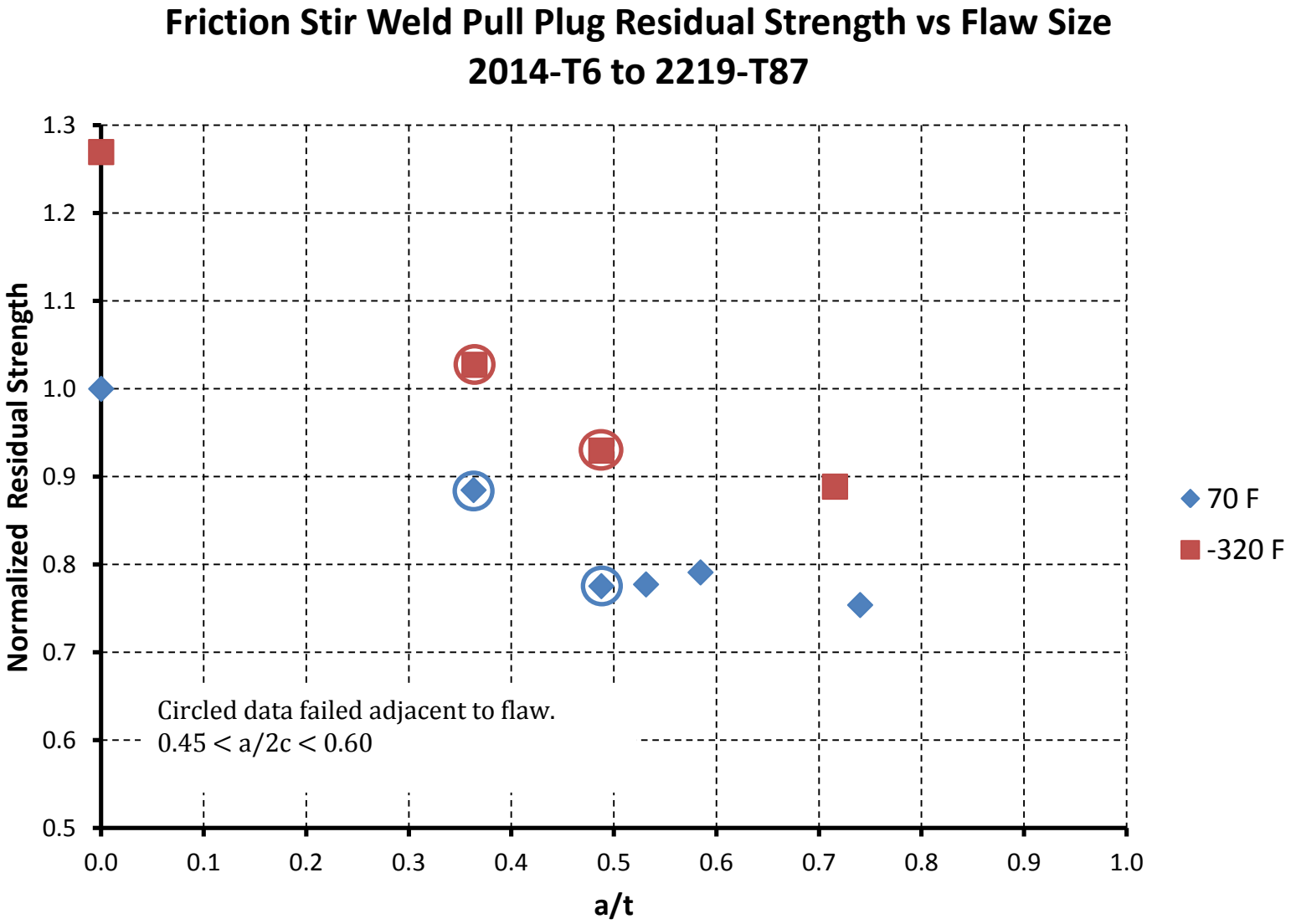
EDM Notch

Ductile tearing during simulated proof cycle

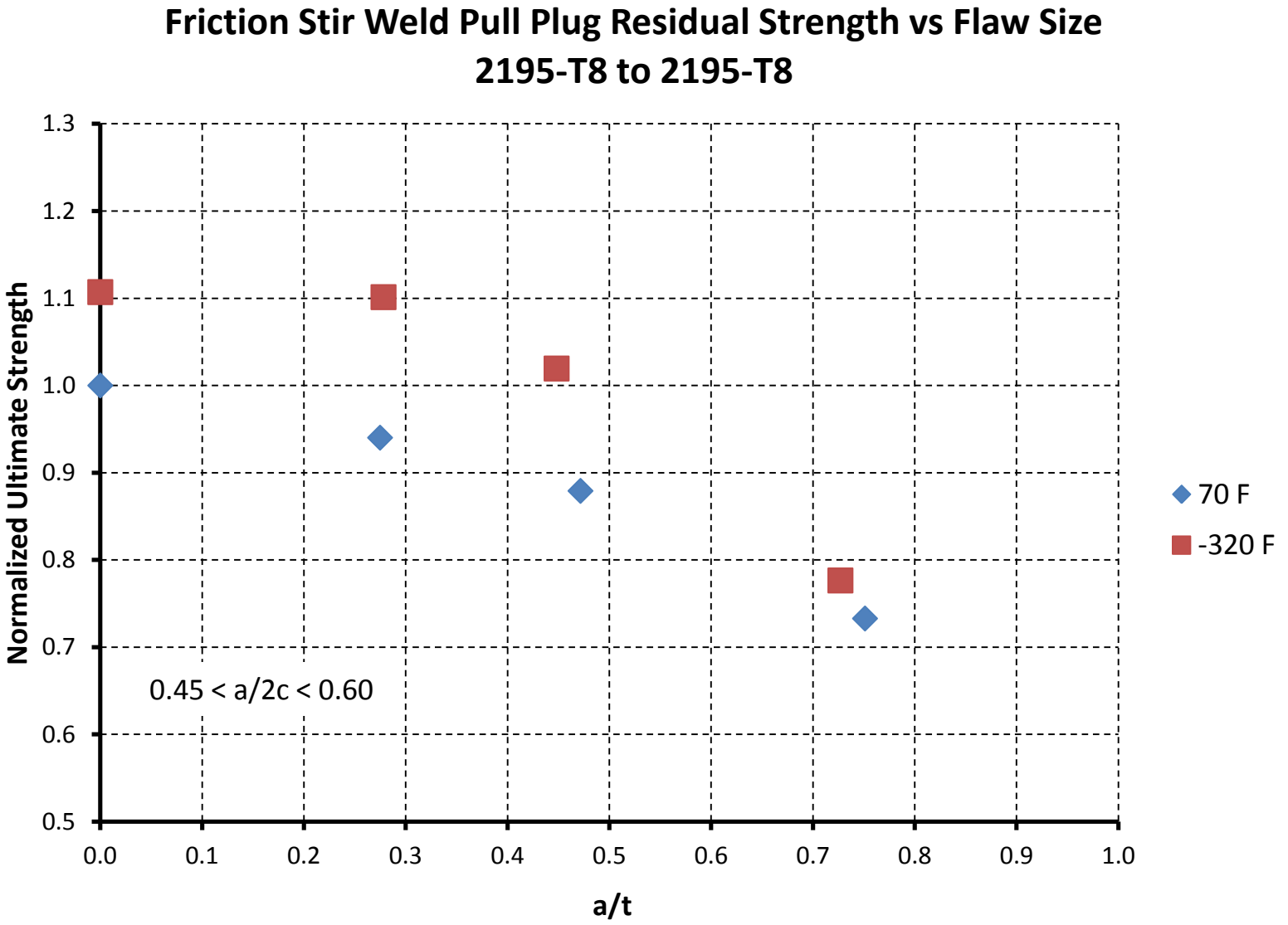


Fracture surface in conventional friction stir weld

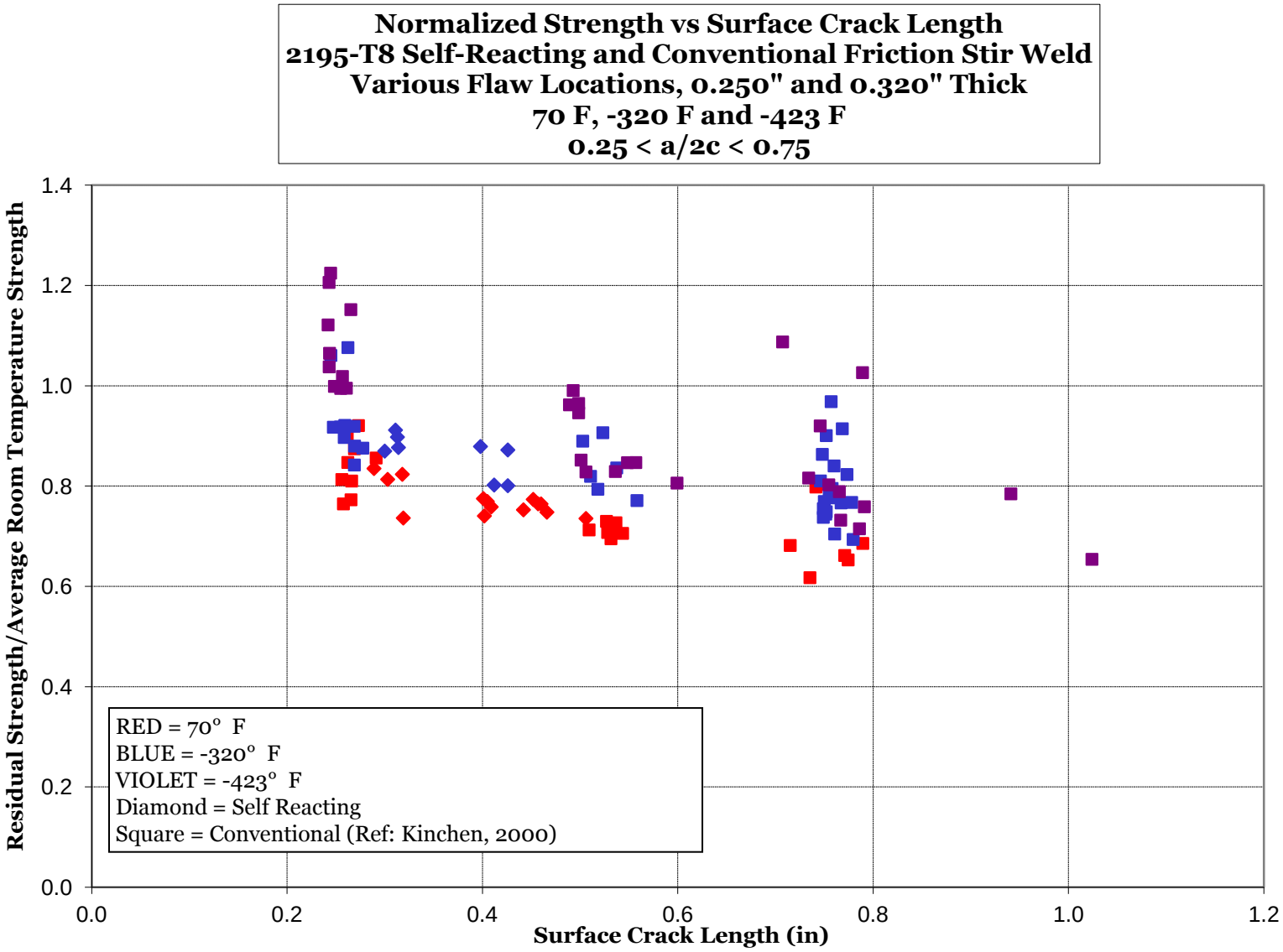
Testing


Friction Stir Weld Pull Plug Residual Strength vs Flaw Size
2014-T6 to 2219-T87
Normalized Residual Strength
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
a/t
Circled data failed adjacent to flaw.
0.45 < a/2c < 0.60
70 F
-320 F

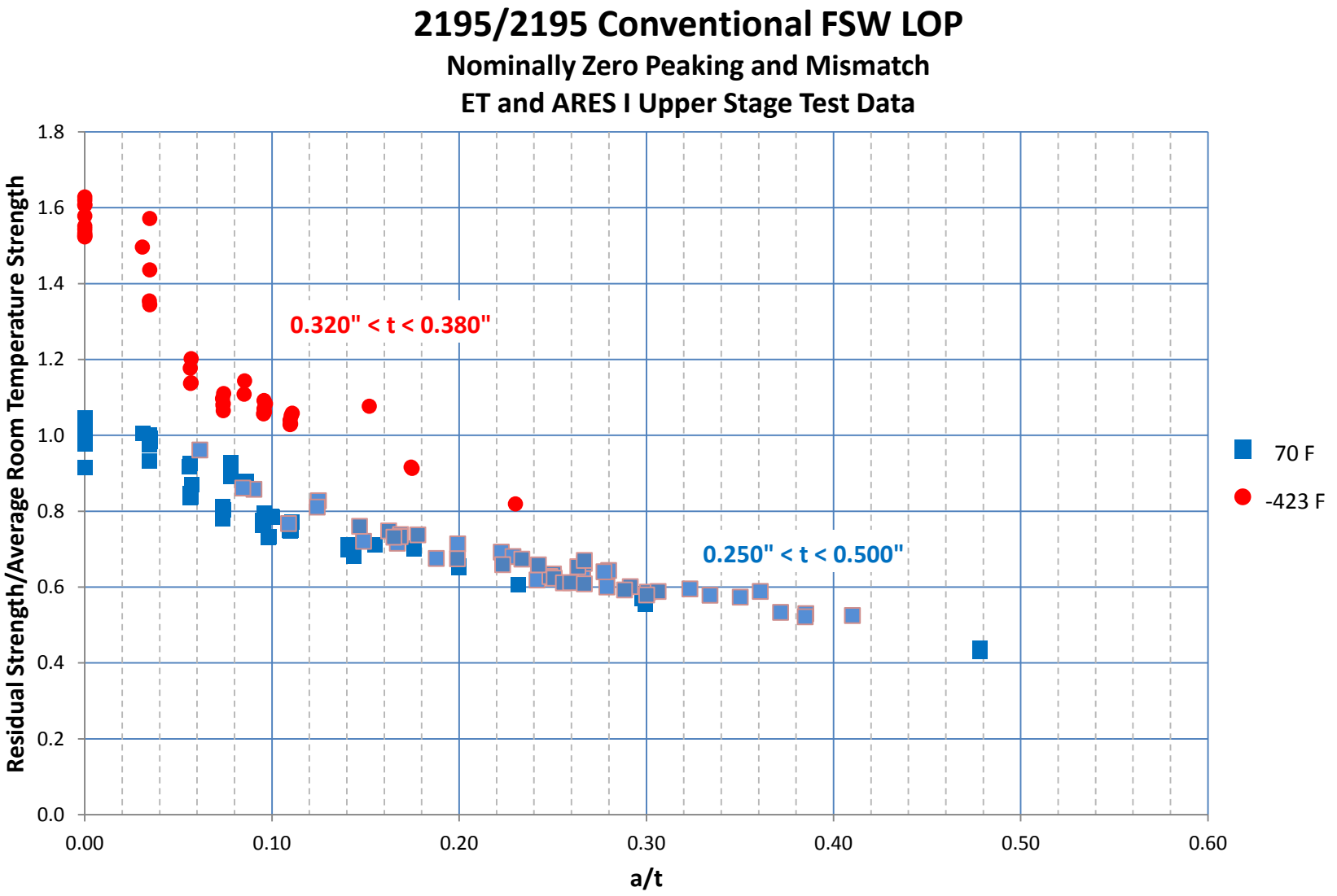
Testing


Friction Stir Weld Pull Plug Residual Strength vs Flaw Size
2195-T8 to 2195-T8
Normalized Ultimate Strength
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
a/t
0.45 < a/2c < 0.60
70 F
-320 F

Testing


Normalized Strength vs Surface Crack Length
2195-T8 Self-Reacting and Conventional Friction Stir Weld
Various Flaw Locations, 0.250" and 0.320" Thick
70 F, -320 F and -423 F
0.25 < a/2c < 0.75
Residual Strength/Average Room Temperature Strength
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Surface Crack Length (in)
RED = 70° F
BLUE = -320° F
VIOLET = -423° F
Diamond = Self Reacting
Square = Conventional (Ref: Kinchen, 2000)

Testing


2195/2195 Conventional FSW LOP
Nominally Zero Peaking and Mismatch
ET and ARES I Upper Stage Test Data
Residual Strength/Average Room Temperature Strength
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.00
0.10
0.20
0.30
0.40
0.50
0.60
a/t
0.320" < t < 0.380"
0.250" < t < 0.500"
70 F
-423 F

Conclusions

- Expanding fracture database for friction stir welds and friction plug welds.
- In general residual cryogenic strength of friction stir welds and friction plug welds is higher than residual ambient strengths
- Critical surface flaws can be reliably detected with liquid penetrant nondestructive evaluation.
- Critical volumetric flaws can be reliably detected with Phased Array Ultrasonic nondestructive evaluation.
- Damage Tolerance Approach
  - Nondestructive Evaluation
    - PAUT
    - Etched Visual
  - Cryogenic toughness greater than room temperature toughness so room temperature proof testing is a viable option for screening mission critical defects.
  - Process Control

References

1. Arthur C. Nunes, Jr. "Friction Stir Welding." *Innovations in Materials Manufacturing, Fabrication, and Environmental Safety,* CRC Press 2011.
2. Kinchen, D., *External Tank Friction Stir Weld Program Technical Presentation*, Lockheed Martin Manned Space Systems, January, 2008.
3. Kinchen, D., ETTR-MS-00-005, *Fracture and Simulated Service Tests of External Tank LO2 and LH2 Barrel Longitudinal Friction Stir Welds, 2000.*
4. Schneider, J.A. Nunes Jr., A. C. and Brendel M.S., *The Influence of Friction Stir Weld Tool Form and Welding Parameters on Weld Structure and Properties: Nugget Bulge in Self-Reacting Friction Stir Welds,* 8th International Symposium on Friction Stir Welding, TWI Ltd., May, 2010.
5. Kinchen, D., *External Tank Weld Technical Interchange,* Lockheed Martin Manned Space Systems, May, 2009.